

RECEIVED: September 26, 2014

REVISED: January 19, 2015

ACCEPTED: January 28, 2015

PUBLISHED: February 23, 2015

Explaining the lepton non-universality at the LHCb and CMS within a unified framework

Sanjoy Biswas^{a,b} Debtoosh Chowdhury,^b Sangeun Han^{c,d} and Seung J. Lee^{c,e}

^a*Dipartimento di Fisica, Università di Roma La Sapienza,
Piazzale Aldo Moro 2, I-00185 Rome, Italy*

^b*Istituto Nazionale di Fisica Nucleare, Sezione di Roma,
Piazzale Aldo Moro 2, I-00185 Rome, Italy*

^c*Department of Physics, Korea Advanced Institute of Science and Technology,
335 Gwahak-ro, Yuseong-gu, Daejeon 305-701, Korea*

^d*Center for Theoretical Physics of the Universe, IBS,
Daejeon, Korea*

^e*School of Physics, Korea Institute for Advanced Study,
Seoul 130-722, Korea*

E-mail: sanjoy.biswas@roma1.infn.it, debtoosh.chowdhury@roma1.infn.it,
gaaearth@kaist.ac.kr, sjjlee@kaist.ac.kr

ABSTRACT: The recent results from the LHCb in the context of $(B^+ \rightarrow K^+ ll)$ decay and the CMS analysis in the context of right handed W -boson (W_R) search show a 2.6σ and a 2.8σ deviations from the Standard Model expectations respectively. In this work, we address these two seemingly uncorrelated results in the context of \mathcal{R} -parity violating supersymmetry. We found that a particular combination of LQD^c -type operators which successfully explain the LHCb result, can also accommodate the CMS excess in the $eejj$ channel of the W_R search.

KEYWORDS: Supersymmetry, Hadron-Hadron Scattering, Beyond Standard Model, B physics, Rare decay

ARXIV EPRINT: [1409.0882](https://arxiv.org/abs/1409.0882)

Contents

1	Introduction	1
2	Model: RPV SUSY	2
3	Phenomenology	3
3.1	Lepton non-universality at the LHCb	3
3.2	Lepton non-universality at the CMS	7
4	Results and discussion	9

1 Introduction

The recent LHCb measurement has observed [1] a significant deviation from the standard model (SM) expectation of the ratio R_K , defined as $R_K = \text{Br}(B^+ \rightarrow K^+ \mu^+ \mu^-) / \text{Br}(B^+ \rightarrow K^+ e^+ e^-)$ [2]. The measurement predicts a 2.6σ deviation from the SM prediction, in the low invariant mass region ($1 \text{ GeV}^2 \leq M_{\ell\ell} \leq 6 \text{ GeV}^2$) of the di-lepton pair using a data set of 3 fb^{-1} integrated luminosity.

More interestingly, CMS analysis for the right-handed W -boson (W_R) search has also come up with a significant deviation from the standard model expectation [3]. The CMS search uses pp collision data at the Large Hadron Collider (LHC) at a center of mass energy of 8 TeV with 19.7 fb^{-1} integrated luminosity. The invariant mass distribution M_{eejj} shows an excess around 2 TeV, with a local significance of 2.8σ [3]. The CMS collaboration has also reported a possible excess in the context of the di-leptoquark search [4]. The optimization of the data assuming a leptoquark mass $\sim 650 \text{ GeV}$ yields a local significance of 2.4σ (2.6σ) in the $eejj$ ($e\nu jj$) channel.

There have already been quite a few studies in an attempt to explain these results separately assuming different models. In ref. [5], the authors studied the observed value of R_K in the context of effective operator approach, illustrated with two leptoquark models. They also mentioned that the leptoquark couplings considered there, can correspond to certain \mathcal{R} -parity violating (RPV) supersymmetric scenario. However the flavor structure of those couplings can not address the CMS $eejj$ excesses. Certain constraints have been put on these effective operators in [6]. On the other hand, the CMS excess in the context of both W_R and di-leptoquark search is interpreted in [7] with a resonant coloron production and further decay of the coloron into a pair of leptoquark and in [8], with resonant production of vector like leptons via W'/Z' vector boson. A similar analysis [9] with W'/Z' has been performed in the context of W_R search. Refs. [10, 11] showed that the W_R excess can be explained within the context of GUT models. Within the framework of \mathcal{R} -parity violating

supersymmetry (SUSY) an explanation via resonant slepton production has been provided in [12] in the context of CMS W_R search. In ref. [13] the di-leptoquark excess is explained.

Though it is quite preliminary to jump into any conclusion before a more detailed analysis of the data and despite of the fact that the statistics is very low in the case of CMS analyses, one can still take these deviations at their face value in order to ensure a better search strategies either to claim a discovery or to put an exclusion limit. It is worth noting that while there are individual explanations for each of these results mentioned above, so far there has been no attempt to have explain both simultaneously. In this article we present a unified framework which can accommodate both the LHCb and the CMS W_R search results in the context of the RPV minimal supersymmetric standard model (MSSM). Given the fact that the deviation in the measured value of R_K can be consistent with new physics (NP) either in the electron or in the muon sector due to the large theoretical uncertainties present in the SM expectations, in this article, we focus on the former possibility motivated by the observed CMS excess.

The remaining of the paper is organized as follows: in section 2, we give a brief account of the RPV model. Section 3 describes both the B -physics and collider consequences of this model. Finally, we summarize our results and conclude in section 4.

2 Model: RPV SUSY

In this section, we will give a brief review of \mathcal{R} -parity violating SUSY scenario. While \mathcal{R} -parity conserving SUSY has many judicious features, which made it one of the most popular frameworks, \mathcal{R} -parity violating SUSY [14–18] provides an alternative. It can relax the naturalness bound from LHC due to the absence of large missing transverse energy (\cancel{E}_T) signature and at the same time provides rich collider phenomenology. In MSSM, the RPV interactions are generated through the following superpotential,

$$\begin{aligned}\mathcal{W}_{\text{hTL}} &= \frac{1}{2}\lambda_{ijk}L_iL_jE_k^c + \lambda'_{ijk}L_iQ_jD_k^c + \frac{1}{2}\lambda''_{ijk}U_i^cD_j^cD_k^c, \\ \mathcal{W}_{\text{hBL}} &= \mu'_iL_iH_u,\end{aligned}\tag{2.1}$$

where L_i , E_i^c denote $\text{SU}(2)_L$ doublet and singlet superfields for leptons respectively, Q_i , U_i^c and D_i^c represent the left-handed quark doublet, right-handed up-type quark singlet and right-handed down-type quark singlet superfield respectively and H_u is the up-type Higgs superfield that gives mass to the up-type quarks. Here, \mathcal{W}_{hTL} are the trilinear terms which contains only dimensionless parameters, and \mathcal{W}_{hBL} denotes the holomorphic bilinear terms containing dimensionful couplings. The λ_{ijk} 's and λ'_{ijk} 's are Lepton number violating and λ''_{ijk} 's are Baryon number violating Yukawa couplings.

In the context of the present study, we will work with only λ'_{ijk} -type of couplings, in particular, with λ'_{112} and λ'_{113} couplings, purely motivated by the observations of LHCb and CMS. We found that it is the only combination of RPV couplings which can be consistent with both of these observations. The coupling constants for the RPV operators are typically small due to the constraints from various observables including proton stability,

neutrino mass and mixing, processes with flavor-changing neutral current and CP violation, cosmological baryon asymmetries, etc. (see e.g. ref. [19] for a comprehensive review). Recently there has been some works for providing an organizing principle that explains why RPV couplings are typically small and hierarchical [20–24]. The choice of our RPV couplings λ'_{11k} with $k = 2$ and 3 , are constrained from various low energy observables such as, (i) charge-current universality, (ii) $e - \mu - \tau$ universality, (iii) atomic parity violation etc. The most stringent bound on individual RPV coupling comes from (i) and (ii) [25, 26]

$$|\lambda'_{11k}| \left(\frac{100 \text{ GeV}}{m_{\tilde{d}_{kR}}} \right) < 0.03, \quad (2.2)$$

where, $m_{\tilde{d}_{kR}}$ is the mass of the right-handed down-type squark.

The bounds on the product $|\lambda'_{112}\lambda'_{113}|$ mainly come from charged B -meson decay $B_d^\pm \rightarrow \pi^\pm K^0$, $B_s - \bar{B}_s$ mixing and $B \rightarrow X_s \gamma$ transition. Assuming the mediator mass to be around 100 GeV these translate to

$$|\lambda'_{112}\lambda'_{113}| \lesssim \begin{cases} 5.7 \times 10^{-3} & [B_d^\pm \rightarrow \pi^\pm K^0][27], \\ 2.3 \times 10^{-2} & [B_s - \bar{B}_s][28], \\ 3.5 \times 10^{-2} & [B \rightarrow X_s \gamma][29, 30]. \end{cases} \quad (2.3)$$

In addition to the known bounds on RPV couplings λ'_{11k} listed above, we present new bounds obtained by analyzing the non-observation of “contact interactions” from collider searches in the following. The collider experiments at the LEP [31], HERA [32] and Tevatron [33, 34] have put some bounds [35] on the cut-off scale of the four-fermion operator, $\frac{4\pi}{\Lambda_{LR}^2}(\bar{e}_L \gamma_\mu e_L)(\bar{q}_R \gamma^\mu q_R)$, with $\{q = s, b\}$: $\Lambda_{LR} \sim 5.2 \text{ TeV}$ for $q = s$ and $\Lambda_{LR} \sim 2.8 \text{ TeV}$ for $q = b$. This imposes the following bounds on the RPV couplings:

$$|\lambda'_{112}| < \frac{m_{\tilde{u}_L}}{1.0 \text{ TeV}}, \quad (2.4)$$

$$|\lambda'_{113}| < \frac{m_{\tilde{u}_L}}{560 \text{ GeV}}. \quad (2.5)$$

Also from a global study of electron-quark contact interactions [36, 37] through ZEUS [38], H1 [39], polarized e^- on nuclei scattering experiments at SLAC [40], Mainz [41], and Bates [42], Drell-Yan production at the Tevatron [43], total hadronic cross section σ_{had} at CERN LEP [44–51], and neutrino-nucleon scattering from CCFR [52], the highest fit value is found to be $\Lambda_{LR} \sim 11.2 \text{ TeV}$, which translates into

$$|\lambda'_{11q}| < \frac{m_{\tilde{u}_L}}{2.2 \text{ TeV}}. \quad (2.6)$$

3 Phenomenology

3.1 Lepton non-universality at the LHCb

We begin with analyzing the recent result on the measurement of R_K reported by the LHCb collaboration. As we aim for finding a unified framework for explaining two seemingly uncorrelated measurements, we restrict our analysis for R_K within the context of $eejj$ excess

reported by CMS in the context of W_R search only. For this, the RPV LQD^c -type λ'_{112} and λ'_{113} couplings are the most important parameters where the former plays a major role in determining the size of both observables. Therefore, in our B -physics analysis we will focus on finding a reasonable parameter space which would allow a sizable λ'_{112} coupling compatible with the CMS $eejj$ data. Here we want to emphasize that this particular combination of RPV operators. We found that all the other possible combinations of RPV operator cannot simultaneously explain both CMS and LHCb results. For example, the combination of λ'_{122} and λ'_{123} can explain the R_K , but fails to accommodate the $eejj$ excess due to low slepton production cross-sections. Therefore, the combination of RPV LQD^c -type λ'_{112} and λ'_{113} couplings provide a unique solution to the problems we consider in our paper.

In the SM, $b \rightarrow s$ flavor changing neutral current transition is in general highly suppressed due to absence of tree level processes. The leading order contribution comes from electroweak loop processes. Therefore, it provides an important tools to test the flavor sector of the SM, as well as to probe and constrain its possible extensions. In this context, for the exclusive decay $B^+ \rightarrow K^+ ll$ with $l = e, \mu$, one of the very useful observables is the ratio (R_K) of the branching fractions in the individual lepton flavor mode.

Theoretically, $R_K \approx 1$ from the lepton universality in the SM, which ensures that electron and muon couple to the gauge bosons with the same strength. Although the individual branching fractions of $B^+ \rightarrow K^+ ee$ and $B^+ \rightarrow K^+ \mu\mu$ suffer from theoretical uncertainties of $\mathcal{O}(30\%)$ [53], R_K remains unaffected as the uncertainties cancel out while taking the ratio [2]. Hence, it is a clean and sensitive observable for probing the extension of the SM, specially for the flavor-non-universality.

The recent measurement of R_K in the low di-lepton invariant mass squared region, $1 \text{ GeV}^2 < q^2 < 6 \text{ GeV}^2$, is found to be [1],

$$R_K^{\text{LHCb}} = 0.745 \pm_{0.074}^{0.090} \pm 0.036. \quad (3.1)$$

This corresponds to a 2.6σ deviation from the SM prediction, $R_K = 1.0003^{+0.00010}_{-0.00007}$ [2, 54], indicating a possible hint of new physics. As discussed in the introduction, there are two possible explanations: it could be either due to the depletion in $\text{Br}(B^+ \rightarrow K^+ \mu\mu)$ or an enhancement in $\text{Br}(B^+ \rightarrow K^+ ee)$. We focus on the latter, in order to explain the CMS $eejj$ excess as well.

We begin with considering the following effective weak Hamiltonian for $\bar{s}bll$ transition,

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i C_i(\mu) \mathcal{O}_i(\mu), \quad (3.2)$$

where α_e , V_{ij} , G_F and μ are the fine structure constant, the CKM matrix elements, the Fermi constant, and the renormalization scale respectively. The relevant dimension six $\bar{s}bll$ operators in our case are vector and axial-vector operators

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l), \quad \mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu \gamma_5 l). \quad (3.3)$$

The corresponding chirality-flipped operators \mathcal{O}' are obtained by changing $P_L \leftrightarrow P_R$. It is convenient to divide the Wilson coefficients as

$$C^{(\prime)}(\mu) = C^{\text{SM}(\prime)}(\mu) + C^{\text{NP}(\prime)}(\mu), \quad (3.4)$$

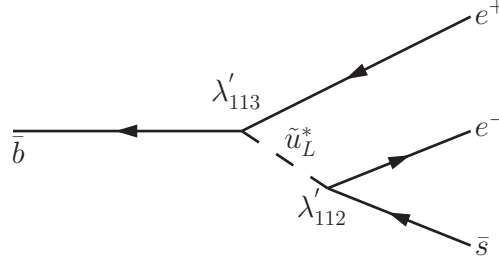


Figure 1. Feynman diagram of $\bar{b} \rightarrow \bar{s} e^+ e^-$ decay via λ'_{113} and λ'_{112} coupling.

where, $C^{\text{SM}(\prime)}(\mu)$ is the SM contribution and $C^{\text{NP}(\prime)}(\mu)$ is the NP contribution. We have $C_9^{\text{SM}}(m_b) = -C_{10}^{\text{SM}}(m_b) = 4.2$ for all leptons while rest of the semileptonic Wilson coefficients are negligible [55]. As described in section 1, in this work we consider the following \mathcal{R} -parity violating term in eq. (2.1) as a source of NP,

$$\mathcal{L} \ni \lambda'_{ijk} L_i Q_j D_k^c. \quad (3.5)$$

In the context of $\bar{b} \rightarrow \bar{s} e e$ transition (figure 1), we analyze the coupling between up-type squark \tilde{u}_L , down-type quarks s and b , and electron,

$$\mathcal{L} \ni \lambda'_{112} \tilde{u}_L (\bar{s} P_L e) + \lambda'_{113} \tilde{u}_L (\bar{b} P_L e) + \text{h.c.} \quad (3.6)$$

Integrating out \tilde{u}_L , we obtain the following effective Hamiltonian

$$\begin{aligned} \mathcal{H}_{\text{eff}} &= -\frac{\lambda'_{112} \lambda_{113}^*}{m_{\tilde{u}_L}^2} (\bar{s} P_L e) (\bar{e} P_R b) \\ &= \frac{\lambda'_{112} \lambda_{113}^*}{2m_{\tilde{u}_L}^2} (\bar{s} \gamma^\mu P_R b) (\bar{e} \gamma_\mu P_L e) \\ &= -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} (C_9^{\prime e} \mathcal{O}_9^{\prime e} + C_{10}^{\prime e} \mathcal{O}_{10}^{\prime e}), \end{aligned} \quad (3.7)$$

where, $m_{\tilde{u}_L}$ is the mass of \tilde{u}_L , and the Wilson coefficients in terms of the RPV operators are given by

$$C_{10}^{\prime e} = -C_9^{\prime e} = \frac{\lambda'_{112} \lambda_{113}^*}{V_{tb} V_{ts}^*} \frac{\pi}{\alpha_e} \frac{\sqrt{2}}{4m_{\tilde{u}_L}^2 G_F}. \quad (3.8)$$

For simplicity, we will suppress the explicit μ dependencies of the Wilson coefficients from here onward. Since we only have the vector and axial-vector operators, it is straightforward to obtain bounds on the relevant parameters from the experimental data.

Here, following the leptoquark model in [5], we focus on fitting R_K exclusively, allowing other observables (e.g. $B \rightarrow K^* l^+ l^-$ [55, 56], $B \rightarrow X_s l^+ l^-$ [57, 58], $B \rightarrow e^+ e^-$ [59, 60], and $B \rightarrow \mu^+ \mu^-$ [59, 61]), affected by the same operators, to be consistent within 1σ region [6]. It is worth noting that several inclusive analyses on these operators, specially in the context of angular observables in $B \rightarrow K^* \mu^+ \mu^-$, have been performed [62–66], as well as a recent global fit with inclusion of R_K [6]. While the current global fit prefers NP to be appearing in left-handed current with muon, rather than in left-handed current operator with electron

we are considering, the tension is only within 1σ range. Therefore, in light of explaining R_K from NP contribution, it is not unreasonable to consider operators involving left-handed electron current as was done in the leptoquark model [5].¹ In addition, when one also addresses the CMS $eejj$ excess at the same time, this choice becomes inevitable.

Following [5, 67], the bound on the Wilson coefficients coming from R_K at 1σ level is given by

$$0.7 \lesssim \text{Re}[X^e - X^\mu] \lesssim 1.5, \quad (3.9)$$

where, $X^e = 2C_9^{\prime e}$ and $X^\mu = 0$ in our case.

The other important bound comes from the \bar{B}_s decay. In the absence of the scalar and pseudoscalar operator, the model independent constraint is given by [5],

$$\frac{\text{Br}(\bar{B}_s \rightarrow ee)^{\text{NP}}}{\text{Br}(\bar{B}_s \rightarrow ee)^{\text{SM}}} = |1 + 0.24 C_{10}^{\prime e}|^2. \quad (3.10)$$

The corresponding experimental data [61] and SM value [59] of $\text{Br}(\bar{B}_s \rightarrow ee)$, and their ratio are given by

$$\text{Br}(\bar{B}_s \rightarrow ee)^{\text{exp}} < 2.8 \times 10^{-7}, \quad (3.11)$$

$$\text{Br}(\bar{B}_s \rightarrow ee)^{\text{SM}} = (8.54 \pm 0.55) \times 10^{-14}, \quad (3.12)$$

$$\frac{\text{Br}(\bar{B}_s \rightarrow ee)^{\text{exp}}}{\text{Br}(\bar{B}_s \rightarrow ee)^{\text{SM}}} < 3.3 \times 10^6. \quad (3.13)$$

From these, we obtain a bound on the Wilson coefficient $C_{10}^{\prime e}$,

$$|1 + 0.24 \cdot C_{10}^{\prime e}|^2 < 3.3 \times 10^6. \quad (3.14)$$

Plugging in the values of input parameters [61], $|V_{tb}| = 0.999146_{-0.000046}^{+0.000021}$, $|V_{ts}| = 0.0404_{-0.0005}^{+0.0011}$, $G_F = 1.1663787 \times 10^{-5} \text{GeV}^{-2}$, and $\alpha_e(m_b) = 1/133$, in eq. (3.8), the Wilson coefficient $C_{9,10}^{\prime e}$ become

$$C_{10}^{\prime e} = -C_9^{\prime e} \simeq -\frac{\lambda'_{112}\lambda_{113}^*}{2m_{\tilde{u}_L}^2}(21 \text{ TeV})^2. \quad (3.15)$$

Substituting this into eq. (3.9) and eq. (3.14), we obtain the following constraints on our model parameters, $m_{\tilde{u}_L}$, λ'_{112} and λ'_{113} ,

$$\frac{0.7}{(21 \text{ TeV})^2} \lesssim \text{Re} \left[\frac{\lambda'_{112}\lambda_{113}^*}{m_{\tilde{u}_L}^2} \right] \lesssim \frac{1.5}{(21 \text{ TeV})^2}, \quad (3.16)$$

$$\left| 1 - 0.12 \frac{\lambda'_{112}\lambda_{113}^*}{m_{\tilde{u}_L}^2} (21 \text{ TeV})^2 \right|^2 < 3.3 \times 10^6. \quad (3.17)$$

The above two equations sets the hierarchy between the two couplings λ'_{112} and λ'_{113} for a fixed value of $m_{\tilde{u}_L}$.

¹For detailed discussion of other B physics observables, see the discussion in [5], specially for section III-A for (Axial)-vectors operator and section IV-A for a model with a RL operator for electrons. Note that, as mentioned in the introduction, this model is just the same as ours except that it's on third generation, and hence cannot explain the CMS excess.

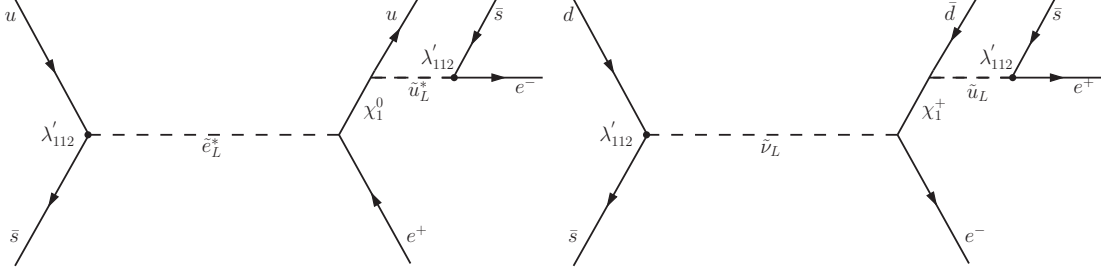


Figure 2. Feynman diagram of (a) resonant selectron production (left) and (b) resonant sneutrino production via λ'_{112} coupling.

3.2 Lepton non-universality at the CMS

We have considered resonant slepton production via λ'_{112} coupling in pp collision at the LHC at 8 TeV center of mass energy with 19.7 fb^{-1} integrated luminosity. The resonant slepton production at collider experiments has been studied extensively in [68–75]. The slepton thus produced can decay via both \mathcal{R} -parity conserving and violating couplings. The branching ratio depends on the mass of the lightest SUSY particle (LSP) and the λ'_{112} coupling. Both the selectron and the sneutrino have a substantial decay branching fraction of decaying into $e\chi_1^0$ and $e\chi_1^+$ respectively. The lightest neutralino and lighter chargino can further decay via the RPV coupling resulting in a $eejj$ final state as studied in the context of the W_R search at CMS [3],

$$pp \rightarrow \tilde{e}_L \rightarrow e\chi_1^0 \rightarrow eejj, \quad (3.18)$$

$$pp \rightarrow \tilde{\nu}_L \rightarrow e\chi_1^+ \rightarrow eejj. \quad (3.19)$$

In figure 2 we show the Feynman diagrams leading to the above final state through the resonant production of selectron (left) and sneutrino (right). We have considered three different benchmark scenarios to take into account the model dependency in the branching ratio calculation:

- **Bino-like scenario:** $M_1 \ll M_2$, the LSP is dominated by the bino-component, with heavy wino mass ($> 2 \text{ TeV}$). In this scenario the branching ratio of the slepton decay via \mathcal{R} -parity conserving coupling can be subdominant compared to the di-jet mode.
- **Mixed scenario:** $M_1 : M_2 = 2 : 3$, i.e., the LSP is mostly bino-like with a small wino-admixture. In this case the slepton has a substantial branching ratio of decaying into second lightest neutralino (χ_2^0) and lighter chargino (χ_1^+). Both the χ_2^0 and χ_1^+ in this case decay via \mathcal{R} -parity conserving coupling, hence reducing the effective $\tilde{\ell}(\tilde{\nu}) \rightarrow eejj$ branching ratio.
- **Mixed inverted scenario:** $M_1 : M_2 = 3 : 2$, i.e., the LSP is mostly wino-like with a small bino-admixture. In this case the slepton has a substantial branching ratio of decaying to the lightest neutralino and lighter chargino. In this scenario, however, both the lighter chargino and the lightest neutralino decay via RPV coupling. Hence,

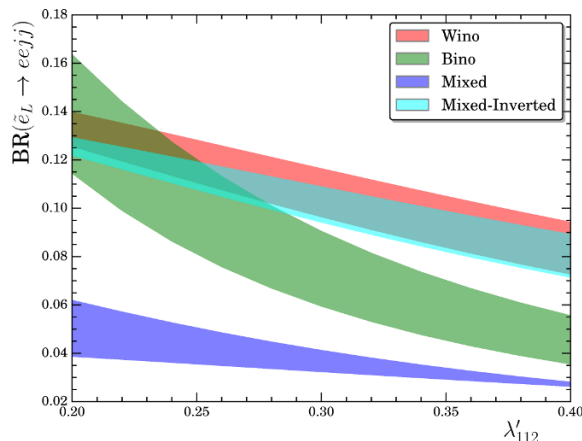


Figure 3. The effective $\text{BR}(\tilde{e}_L \rightarrow eejj)$ vs. λ'_{112} plot for bino, mixed, mixed-inverted and wino-like scenarios. Each color band corresponds to the neutralino mass varied within the range [300, 1000] GeV.

the lepton and jet multiplicity get enhanced in the final state compared to the above two cases.

- **Wino-like scenario:** $M_2 \ll M_1$, i.e., the LSP is purely wino-like. This scenario is similar to above (mixed-inverted) one with a slight enhancement in the effective $\tilde{\ell}(\tilde{\nu}) \rightarrow eejj$ branching ratio.

The model spectrum and decay branching ratios have been calculated using SARAH-4.3.1 [76, 77] and SPheno-3.3.2 [78, 79]. In figure 3 we present the effective $\tilde{e}_L \rightarrow eejj$ branching ratio vs. λ'_{112} . For the rest of the work we will assume the lighter slepton masses of the first generation $m_{\tilde{e}_L, \tilde{\nu}_L} = 2.1$ TeV and dominantly left-chiral. Squark masses of first generation are ~ 1.5 TeV and rest of the sfermions are set at higher values than these. We vary the lightest neutralino mass in the range [300, 1000] GeV. The bound coming from the narrow di-jet resonance search by CMS [80] on the $\sigma \times \text{Br}(\tilde{\ell} \rightarrow jj) \times \mathcal{A}$, where, \mathcal{A} is the efficiency of cut, is 45 fb^{-1} for a resonant mass around 2.1 TeV. The choice of our coupling ranges ($0.2 \leq \lambda'_{112} \leq 0.4$) are consistent with the above bound.

We have simulated the resonant slepton production in pp collision at the LHC using MadGraph5 [81] and the subsequent decays, initial and final state radiation, parton showering and hadronization effects have been done using PYTHIA (v6.4) [82]. We have worked with CTEQ6L [83] parton distribution function. The factorization and the renormalization scales are set at the slepton mass $\mu_F = \mu_R = m_{\tilde{e}_L}$. To take into account the next-to-leading order QCD correction we multiply the tree-level cross-section by the K -factor 1.34 [74]. We have also used various resolution functions parametrized as in [84] for the final state objects to model the finite detector resolution effects. We have assumed the object definition described in [3] for the final state particles along with the following cuts,

- Invariant mass of the electron pair, $M_{ee} > 200$ GeV.
- Invariant mass of the two electrons and dijet system, $M_{eejj} > 600$ GeV.

Cut	Signal	Background	Data
$2e+ \geq 2j$	11.72	34154	34506
$M_{ee} > 200 \text{ GeV}$	11.71	1747	1717
$M_{eejj} > 600 \text{ GeV}$	11.71	783 ± 51	817
$1.8 \text{ TeV} < M_{eejj} < 2.2 \text{ TeV}$	10.01	4.0 ± 1.0	14

Table 1. Number of events from signal, backgrounds and reconstructed data assuming $\lambda'_{112} = 0.22$, $m_{\tilde{e}_L} = 2.1 \text{ TeV}$ and $m_{\chi_1^0} = 400 \text{ GeV}$ in the wino-like benchmark scenario at 19.7 fb^{-1} integrated luminosity and 8 TeV center of mass energy. The data, SM backgrounds and selection cuts are taken from ref. [3].

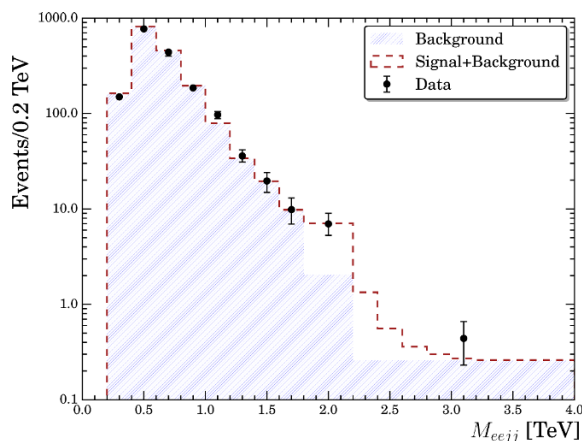


Figure 4. A comparison of the data, signal and background of the M_{eejj} distributions after imposing cuts used in analysis of the W_R search. The signal point corresponds to $\lambda'_{112} = 0.22$, $m_{\tilde{e}_L} = 2.1 \text{ TeV}$ and $m_{\chi_1^0} = 400 \text{ GeV}$ in the wino-like benchmark scenarios. The data and SM backgrounds are taken from [3].

4 Results and discussion

In this article, we have addressed the recent CMS and LHCb results from a unified framework. The results of our analysis are shown in table 1 and figure 4 which show the comparison of signal, background and the corresponding data for a typical benchmark point of wino-like scenario. A more detailed analysis depicting the range of λ'_{112} coupling which can be compatible with the CMS result is presented in figure 5. From figure 5a, one can see that there are two distinct regions corresponding to low values of $m_{\chi_1^0}$ where one does have 2.8σ significance in the bino-like scenario. The color gradient in figure 5 signifies the $S/\sqrt{S+B}$ estimate² of the signal where, S is the signal event and B is the background event within $1.8 \text{ TeV} \leq M_{eejj} \leq 2.2 \text{ TeV}$. This is due to the fact that, the cross-section grows with $|\lambda'_{112}|^2$, whereas the \mathcal{R} -parity conserving decay branching ratios of the slepton falls with the increase in λ'_{112} (see figure 3). Thus two regions have been obtained which

²The significance defined here is different from that used by the CMS collaboration. However, we work with this simple definition to find the potential region of parameter space that can explain the CMS excess.

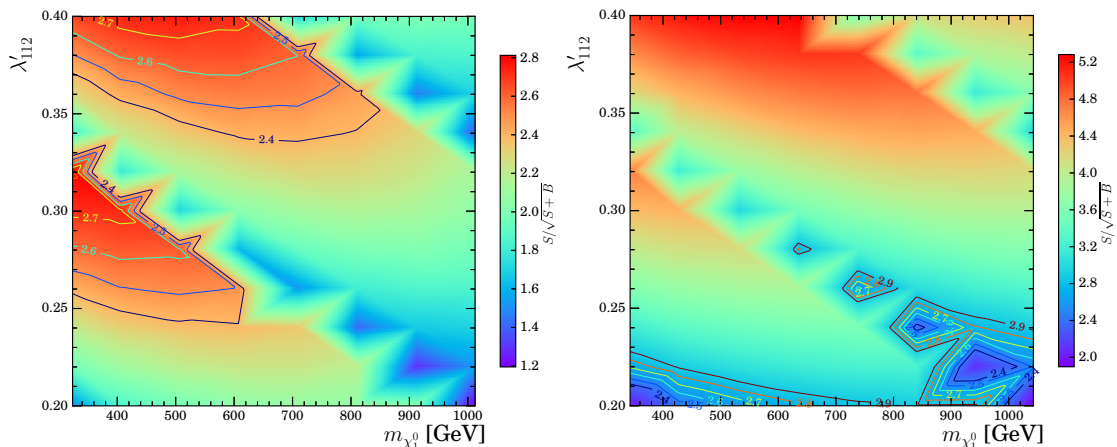


Figure 5. The region of λ'_{112} - $m_{\chi_1^0}$ parameter space compatible with the CMS excess (W_R search) for the (a) bino (left) and (b) wino-like (right) scenario. The color gradient signify the $S/\sqrt{S+B}$ estimate of the signal where, S is the signal event and B is the background event within $1.8 \text{ TeV} \leq M_{eejj} \leq 2.2 \text{ TeV}$. It is not possible to explain the CMS excess assuming the mixed scenario due to a very small effective branching fraction $\text{BR}(\tilde{e}_L \rightarrow eejj)$. The mixed-inverted scenario also gives similar excess as in wino-like scenario.

give equal event rates in the $eejj$ analysis. For the bino-like scenario and the mixed scenario the contribution to $eejj$ final state mainly comes from resonant selectron production (figure 2a). The contribution from the resonant sneutrino production is negligible due to the fact that the RPV decay of the chargino (see figure 2b) has a very small branching ratio.

We can see from figure 5b the allowed value of λ'_{112} is smaller compared to the bino-like case owing to the fact that additional contribution coming from resonant sneutrino production and also enhanced effective branching ratio of $\text{BR}(\tilde{e}_L \rightarrow eejj)$ compared to the bino-like scenario. Note that both the low and high values of the neutralino mass for a $\lambda'_{112} \sim 0.21$ give same excess compatible with the CMS result. This can be explained by the fact that the reduced branching ratio for $m_{\chi_1^0} \sim 1 \text{ TeV}$ is compensated with a higher cut-efficiency.

We emphasize here that the CMS excess has reported the data summed over bins having total width of 400 GeV. The distribution of the data within this range is yet unknown. A fine binning of data is required at high luminosity run. In case the data is distributed over this wide range, a resonance explanation of a given mass may not be a good option. However, the wino and mixed-inverted scenario can be better suited in such a case. This requires a splitting $\mathcal{O}(10^2 \text{ GeV})$ between the selectron and the sneutrino which can be achieved by introducing large RPV soft-terms of the same type.

The CMS $eejj$ excess constrains the λ'_{112} coupling independent of the LHCb result. We use the results discussed above to constrain the parameter space of B -physics analysis, namely, the λ'_{113} coupling and relevant mass parameter ($m_{\tilde{u}_L}$). Figure 6 shows plot in the λ'_{113} - $m_{\tilde{u}_L}$ plane consistent with the experimental data coming from the measurements listed in section 3.1 assuming two fixed values of $\lambda'_{112} = 0.2$ and 0.4 . The present LHC bound on $m_{\tilde{u}_L}$ ($> 1 \text{ TeV}$) in presence of λ' couplings comes from the di-leptoquark search analysis [4]. This leaves us with the choice of λ'_{113} as low as 0.006 (0.0125) for $\lambda'_{112} = 0.4$ (0.2).

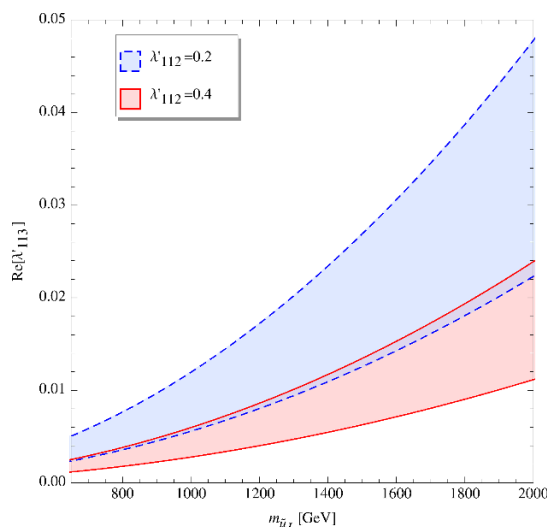


Figure 6. The allowed parameter space in the $m_{\tilde{u}_L} - \text{Re}[\lambda'_{113}]$ plane consistent with the measurement of R_K at LHCb and other B -physics observations discussed in section 3.1. The blue (red) colored region corresponds to $\lambda'_{112} = 0.2$ (0.4).

In summary, our important observation is that the RPV SUSY operator which can explain the lepton non-universality hinted by the measurement of R_K from LHCb, can easily accommodate the lepton non-universality observed by CMS in the context of W_R search. In this analysis we do not address the CMS $eejj$ and $e\nu jj$ excesses in the context of di-leptoquark search. A dedicated analysis [85] will be presented to verify whether the CMS di-leptoquark result can be accommodated within this framework or not. We note that, future measurements in all these sectors can tell us with certainty whether the current deviations are robust or not. As an outlook, we also suggest few collider signatures such as, lepton charge asymmetry measurement in the $e\nu jj$ -channel and ratio of same-sign di-lepton events to opposite-sign di-lepton events in the $eejj$ channel to further discriminate our scenario at the LHC. Our result in the context of R_K will be confronted with all the other B -physics observables, which might further constrain the allowed range of the parameter space of the model considered here. The effective operators considered here may also give rise to rare B -decays like $b \rightarrow s\nu\bar{\nu}$ [86], which could be a promising channel for future B -physics experiments.

Acknowledgments

We would like to thank Luca Silvestrini for useful inputs. SL would like to express a special thanks to the Mainz Institute for Theoretical Physics (MITP) for its hospitality and support. SL is also grateful to the Dipartimento di Fisica, Università di Roma La Sapienza for its hospitality during the completion of this work. SB would like to thank Subhadeep Mondal regarding computational help. DC is supported by the European Research Council under the European Union’s Seventh Framework Programme (FP/2007-2013)/ERC Grant

Agreement n. 279972. SL is supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MEST) (No. 2012R1A2A2A01045722).

Open Access. This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY 4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References

- [1] LHCb collaboration, *Test of lepton universality using $B^+ \rightarrow K^+ \ell^+ \ell^-$ decays*, *Phys. Rev. Lett.* **113** (2014) 151601 [[arXiv:1406.6482](#)] [[INSPIRE](#)].
- [2] G. Hiller and F. Krüger, *More model independent analysis of $b \rightarrow s$ processes*, *Phys. Rev. D* **69** (2004) 074020 [[hep-ph/0310219](#)] [[INSPIRE](#)].
- [3] CMS collaboration, *Search for heavy neutrinos and W bosons with right-handed couplings in proton-proton collisions at $\sqrt{s} = 8$ TeV*, *Eur. Phys. J. C* **74** (2014) 3149 [[arXiv:1407.3683](#)] [[INSPIRE](#)].
- [4] CMS collaboration, *Search for pair-production of first generation scalar leptoquarks in pp collisions at $\sqrt{s} = 8$ TeV*, [CMS-PAS-EXO-12-041](#), CERN, Geneva Switzerland (2012).
- [5] G. Hiller and M. Schmaltz, *R_K and future $b \rightarrow s \ell \ell$ physics beyond the standard model opportunities*, *Phys. Rev. D* **90** (2014) 054014 [[arXiv:1408.1627](#)] [[INSPIRE](#)].
- [6] D. Ghosh, M. Nardecchia and S.A. Renner, *Hint of lepton flavour non-universality in B meson decays*, *JHEP* **12** (2014) 131 [[arXiv:1408.4097](#)] [[INSPIRE](#)].
- [7] Y. Bai and J. Berger, *Coloron-assisted leptoquarks at the LHC*, [arXiv:1407.4466](#) [[INSPIRE](#)].
- [8] B.A. Dobrescu and A. Martin, *Interpretations of anomalous LHC events with electrons and jets*, [arXiv:1408.1082](#) [[INSPIRE](#)].
- [9] J.A. Aguilar-Saavedra and F.R. Joaquim, *Closer look at the possible CMS signal of a new gauge boson*, *Phys. Rev. D* **90** (2014) 115010 [[arXiv:1408.2456](#)] [[INSPIRE](#)].
- [10] F.F. Deppisch, T.E. Gonzalo, S. Patra, N. Sahu and U. Sarkar, *Signal of right-handed charged gauge bosons at the LHC?*, *Phys. Rev. D* **90** (2014) 053014 [[arXiv:1407.5384](#)] [[INSPIRE](#)].
- [11] M. Heikinheimo, M. Raidal and C. Spethmann, *Testing right-handed currents at the LHC*, *Eur. Phys. J. C* **74** (2014) 3107 [[arXiv:1407.6908](#)] [[INSPIRE](#)].
- [12] B. Allanach, S. Biswas, S. Mondal and M. Mitra, *Explaining a CMS $eejj$ excess with R -parity violating supersymmetry and implications for neutrinoless double beta decay*, *Phys. Rev. D* **91** (2015) 011702 [[arXiv:1408.5439](#)] [[INSPIRE](#)].
- [13] E.J. Chun, S. Jung, H.M. Lee and S.C. Park, *Stop and sbottom LSP with R -parity violation*, *Phys. Rev. D* **90** (2014) 115023 [[arXiv:1408.4508](#)] [[INSPIRE](#)].
- [14] L.J. Hall and M. Suzuki, *Explicit R -parity breaking in supersymmetric models*, *Nucl. Phys. B* **231** (1984) 419 [[INSPIRE](#)].
- [15] G.G. Ross and J.W.F. Valle, *Supersymmetric models without R -parity*, *Phys. Lett. B* **151** (1985) 375 [[INSPIRE](#)].
- [16] V.D. Barger, G.F. Giudice and T. Han, *Some new aspects of supersymmetry R -parity violating interactions*, *Phys. Rev. D* **40** (1989) 2987 [[INSPIRE](#)].

- [17] H.K. Dreiner, *An introduction to explicit R-parity violation*, *Adv. Ser. Direct. High Energy Phys.* **21** (2010) 565 [[hep-ph/9707435](#)] [[INSPIRE](#)].
- [18] G. Bhattacharyya, *A brief review of R-parity violating couplings*, [hep-ph/9709395](#) [[INSPIRE](#)].
- [19] R. Barbier et al., *R-parity violating supersymmetry*, *Phys. Rept.* **420** (2005) 1 [[hep-ph/0406039](#)] [[INSPIRE](#)].
- [20] E. Nikolidakis and C. Smith, *Minimal flavor violation, seesaw and R-parity*, *Phys. Rev. D* **77** (2008) 015021 [[arXiv:0710.3129](#)] [[INSPIRE](#)].
- [21] C. Csáki, Y. Grossman and B. Heidenreich, *MFV SUSY: a natural theory for R-parity violation*, *Phys. Rev. D* **85** (2012) 095009 [[arXiv:1111.1239](#)] [[INSPIRE](#)].
- [22] C. Csáki, E. Kuflik and T. Volansky, *Dynamical R-parity violation*, *Phys. Rev. Lett.* **112** (2014) 131801 [[arXiv:1309.5957](#)] [[INSPIRE](#)].
- [23] H.K. Dreiner and M. Thormeier, *Supersymmetric Froggatt-Nielsen models with baryon and lepton number violation*, *Phys. Rev. D* **69** (2004) 053002 [[hep-ph/0305270](#)] [[INSPIRE](#)].
- [24] A. Monteux, *Natural, R-parity violating supersymmetry and horizontal flavor symmetries*, *Phys. Rev. D* **88** (2013) 045029 [[arXiv:1305.2921](#)] [[INSPIRE](#)].
- [25] Y. Kao and T. Takeuchi, *Constraints on R-parity violation from recent Belle/Babar data*, [arXiv:0909.0042](#) [[INSPIRE](#)].
- [26] Y. Kao and T. Takeuchi, *Single-coupling bounds on R-parity violating supersymmetry, an update*, [arXiv:0910.4980](#) [[INSPIRE](#)].
- [27] G. Bhattacharyya and A. Datta, *Effects of R-parity violation on direct CP-violation in B decays and extraction of gamma*, *Phys. Rev. Lett.* **83** (1999) 2300 [[hep-ph/9903490](#)] [[INSPIRE](#)].
- [28] HEAVY FLAVOR AVERAGING GROUP collaboration, Y. Amhis et al., *Averages of B-hadron, C-hadron and τ -lepton properties as of early 2012*, [arXiv:1207.1158](#) [[INSPIRE](#)].
- [29] B. de Carlos and P.L. White, *R-parity violation and quark flavor violation*, *Phys. Rev. D* **55** (1997) 4222 [[hep-ph/9609443](#)] [[INSPIRE](#)].
- [30] H.K. Dreiner, K. Nickel and F. Staub, *$B_{s,d}^0 \rightarrow \mu\bar{\mu}$ and $B \rightarrow X_s\gamma$ in the R-parity violating MSSM*, *Phys. Rev. D* **88** (2013) 115001 [[arXiv:1309.1735](#)] [[INSPIRE](#)].
- [31] ALEPH collaboration, S. Schael et al., *Fermion pair production in e^+e^- collisions at 189–209 GeV and constraints on physics beyond the standard model*, *Eur. Phys. J. C* **49** (2007) 411 [[hep-ex/0609051](#)] [[INSPIRE](#)].
- [32] H1 and ZEUS collaboration, R. Ciesielski, *Search for leptoquarks and contact interactions at HERA*, *PoS(EPS-HEP 2009)269* [[INSPIRE](#)].
- [33] D0 collaboration, V. Abazov et al., *Search for quark-lepton compositeness in the dimuon channel with 400 pb $^{-1}$ D0 Run II data*, D0 note 4922-CONF, Fermilab, Batavia U.S.A. (2005).
- [34] D0 collaboration, V. Abazov et al., *Search for quark-electron compositeness in e^+e^- production*, D0 note 4552-CONF, Fermilab, Batavia U.S.A. (2004).
- [35] M. Carpentier and S. Davidson, *Constraints on two-lepton, two quark operators*, *Eur. Phys. J. C* **70** (2010) 1071 [[arXiv:1008.0280](#)] [[INSPIRE](#)].

- [36] V.D. Barger, K.-M. Cheung, K. Hagiwara and D. Zeppenfeld, *Global study of electron-quark contact interactions*, *Phys. Rev. D* **57** (1998) 391 [[hep-ph/9707412](#)] [[INSPIRE](#)].
- [37] K.-M. Cheung, *Constraints on electron quark contact interactions*, [hep-ph/9807483](#) [[INSPIRE](#)].
- [38] ZEUS collaboration, J. Breitweg et al., *Comparison of ZEUS data with standard model predictions for $e^+p \rightarrow e^+X$ scattering at high x and Q^2* , *Z. Phys. C* **74** (1997) 207 [[hep-ex/9702015](#)] [[INSPIRE](#)].
- [39] H1 collaboration, C. Adloff et al., *Observation of events at very high Q^2 in ep collisions at HERA*, *Z. Phys. C* **74** (1997) 191 [[hep-ex/9702012](#)] [[INSPIRE](#)].
- [40] C.Y. Prescott et al., *Further measurements of parity nonconservation in inelastic electron scattering*, *Phys. Lett. B* **84** (1979) 524 [[INSPIRE](#)].
- [41] W. Heil et al., *Improved limits on the weak, neutral, hadronic axial vector coupling constants from quasielastic scattering of polarized electrons*, *Nucl. Phys. B* **327** (1989) 1 [[INSPIRE](#)].
- [42] P.A. Souder et al., *Measurement of parity violation in the elastic scattering of polarized electrons from ^{12}C* , *Phys. Rev. Lett.* **65** (1990) 694 [[INSPIRE](#)].
- [43] CDF collaboration, F. Abe et al., *Limits on quark-lepton compositeness scales from dileptons produced in 1.8 TeV $p\bar{p}$ collisions*, *Phys. Rev. Lett.* **79** (1997) 2198 [[INSPIRE](#)].
- [44] LEP ELECTROWEAK WORKING GROUP and SLD HEAVY FLAVOR GROUP collaborations, D. Abbaneo et al., *A combination of preliminary electroweak measurements and constraints on the standard model*, [CERN-PPE-96-183](#), CERN, Geneva Switzerland (1996).
- [45] OPAL collaboration, G. Alexander et al., *Measurement of cross-sections and asymmetries in e^+e^- collisions at 130 GeV–140 GeV center-of-mass energy*, *Phys. Lett. B* **376** (1996) 232 [[INSPIRE](#)].
- [46] OPAL collaboration, G. Alexander et al., *Test of the four fermion contact interaction in e^+e^- collisions at 130 GeV–140 GeV*, *Phys. Lett. B* **387** (1996) 432 [[INSPIRE](#)].
- [47] OPAL collaboration, K. Ackerstaff et al., *Production of fermion pair events in e^+e^- collisions at 161 GeV center-of-mass energy*, *Phys. Lett. B* **391** (1997) 221 [[INSPIRE](#)].
- [48] L3 collaboration, M. Acciarri et al., *Measurement of hadron and lepton pair production at $130\text{ GeV} < \sqrt{s} < 140\text{ GeV}$ at LEP*, *Phys. Lett. B* **370** (1996) 195 [[INSPIRE](#)].
- [49] L3 collaboration, M. Acciarri et al., *Measurement of hadron and lepton pair production at $161\text{ GeV} < \sqrt{s} < 172\text{ GeV}$ at LEP*, *Phys. Lett. B* **407** (1997) 361 [[INSPIRE](#)].
- [50] ALEPH collaboration, D. Buskulic et al., *Measurement of hadron and lepton pair production from e^+e^- annihilation at center-of-mass energies of 130 GeV and 136 GeV*, *Phys. Lett. B* **378** (1996) 373 [[INSPIRE](#)].
- [51] P. Langacker and J. Erler, *Unification or compositeness?*, [hep-ph/9703428](#) [[INSPIRE](#)].
- [52] CCFR, E744 and E770 collaborations, K.S. McFarland et al., *A precision measurement of electroweak parameters in neutrino-nucleon scattering*, *Eur. Phys. J. C* **1** (1998) 509 [[hep-ex/9701010](#)] [[INSPIRE](#)].
- [53] C. Bobeth, G. Hiller, D. van Dyk and C. Wacker, *The decay $B \rightarrow K\ell^+\ell^-$ at low hadronic recoil and model-independent $\Delta B = 1$ constraints*, *JHEP* **01** (2012) 107 [[arXiv:1111.2558](#)] [[INSPIRE](#)].

- [54] C. Bobeth, G. Hiller and G. Piranishvili, *Angular distributions of $\bar{B} \rightarrow K\bar{\ell}\ell$ decays*, *JHEP* **12** (2007) 040 [[arXiv:0709.4174](#)] [[INSPIRE](#)].
- [55] C. Bobeth, G. Hiller and D. van Dyk, *General analysis of $\bar{B} \rightarrow \bar{K}^{(*)}\ell^+\ell^-$ decays at low recoil*, *Phys. Rev. D* **87** (2013) 034016 [[arXiv:1212.2321](#)] [[INSPIRE](#)].
- [56] LHCb collaboration, *Differential branching fraction and angular analysis of the $B^+ \rightarrow K^+\mu^+\mu^-$ decay*, *JHEP* **02** (2013) 105 [[arXiv:1209.4284](#)] [[INSPIRE](#)].
- [57] T. Huber, E. Lunghi, M. Misiak and D. Wyler, *Electromagnetic logarithms in $\bar{B} \rightarrow X_s\ell^+\ell^-$* , *Nucl. Phys. B* **740** (2006) 105 [[hep-ph/0512066](#)] [[INSPIRE](#)].
- [58] BABAR collaboration, J.P. Lees et al., *Measurement of the $B \rightarrow X_s\ell^+\ell^-$ branching fraction and search for direct CP-violation from a sum of exclusive final states*, *Phys. Rev. Lett.* **112** (2014) 211802 [[arXiv:1312.5364](#)] [[INSPIRE](#)].
- [59] C. Bobeth et al., *$B_{s,d} \rightarrow \ell^+\ell^-$ in the standard model with reduced theoretical uncertainty*, *Phys. Rev. Lett.* **112** (2014) 101801 [[arXiv:1311.0903](#)] [[INSPIRE](#)].
- [60] CMS and LHCb collaborations, *Combination of results on the rare decays $B_{(s)}^0 \rightarrow \mu^+\mu^-$ from the CMS and LHCb experiments*, CMS-PAS-BPH-13-007, CERN, Geneva Switzerland (2013).
- [61] PARTICLE DATA GROUP collaboration, J. Beringer et al., *Review of particle physics (RPP)*, *Phys. Rev. D* **86** (2012) 010001 [[INSPIRE](#)].
- [62] R. Alonso, B. Grinstein and J. Martin Camalich, *SU(2) \times U(1) gauge invariance and the shape of new physics in rare B decays*, *Phys. Rev. Lett.* **113** (2014) 241802 [[arXiv:1407.7044](#)] [[INSPIRE](#)].
- [63] S. Descotes-Genon, J. Matias and J. Virto, *Understanding the $B \rightarrow K^*\mu^+\mu^-$ anomaly*, *Phys. Rev. D* **88** (2013) 074002 [[arXiv:1307.5683](#)] [[INSPIRE](#)].
- [64] W. Altmannshofer and D.M. Straub, *New physics in $B \rightarrow K^*\mu\mu$?*, *Eur. Phys. J. C* **73** (2013) 2646 [[arXiv:1308.1501](#)] [[INSPIRE](#)].
- [65] F. Beaujean, C. Bobeth and D. van Dyk, *Comprehensive Bayesian analysis of rare (semi)leptonic and radiative B decays*, *Eur. Phys. J. C* **74** (2014) 2897 [[arXiv:1310.2478](#)] [[INSPIRE](#)].
- [66] R.R. Horgan, Z. Liu, S. Meinel and M. Wingate, *Calculation of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ and $B_s^0 \rightarrow \phi\mu^+\mu^-$ observables using form factors from lattice QCD*, *Phys. Rev. Lett.* **112** (2014) 212003 [[arXiv:1310.3887](#)] [[INSPIRE](#)].
- [67] D. Das, G. Hiller, M. Jung and A. Shires, *The $\bar{B} \rightarrow \bar{K}\pi\ell\ell$ and $\bar{B}_s \rightarrow \bar{K}K\ell\ell$ distributions at low hadronic recoil*, *JHEP* **09** (2014) 109 [[arXiv:1406.6681](#)] [[INSPIRE](#)].
- [68] S. Dimopoulos, R. Esmailzadeh, L.J. Hall and G.D. Starkman, *Cross-sections for lepton and baryon number violating processes from supersymmetry at $p\bar{p}$ colliders*, *Phys. Rev. D* **41** (1990) 2099 [[INSPIRE](#)].
- [69] J.L. Hewett and T.G. Rizzo, *Resonant slepton production at hadron colliders in R-parity violating models*, [hep-ph/9809525](#) [[INSPIRE](#)].
- [70] H.K. Dreiner, P. Richardson and M.H. Seymour, *Resonant slepton production*, [hep-ph/9903419](#) [[INSPIRE](#)].
- [71] H.K. Dreiner, P. Richardson and M.H. Seymour, *Resonant slepton production at the LHC*, [hep-ph/0001224](#) [[INSPIRE](#)].

- [72] H.K. Dreiner, P. Richardson and M.H. Seymour, *Resonant slepton production in hadron hadron collisions*, *Phys. Rev. D* **63** (2001) 055008 [[hep-ph/0007228](#)] [[INSPIRE](#)].
- [73] B.C. Allanach, M. Guchait and K. Sridhar, *Resonant slepton production at the LHC in models with an ultralight gravitino*, *Phys. Lett. B* **586** (2004) 373 [[hep-ph/0311254](#)] [[INSPIRE](#)].
- [74] H.K. Dreiner and T. Stefaniak, *Bounds on R-parity violation from resonant slepton production at the LHC*, *Phys. Rev. D* **86** (2012) 055010 [[arXiv:1201.5014](#)] [[INSPIRE](#)].
- [75] B.C. Allanach, C.H. Kom and H. Pas, *Large Hadron Collider probe of supersymmetric neutrinoless double beta decay mechanism*, *Phys. Rev. Lett.* **103** (2009) 091801 [[arXiv:0902.4697](#)] [[INSPIRE](#)].
- [76] F. Staub, *From superpotential to model files for FeynArts and CalcHep/CompHEP*, *Comput. Phys. Commun.* **181** (2010) 1077 [[arXiv:0909.2863](#)] [[INSPIRE](#)].
- [77] F. Staub, *Automatic calculation of supersymmetric renormalization group equations and self energies*, *Comput. Phys. Commun.* **182** (2011) 808 [[arXiv:1002.0840](#)] [[INSPIRE](#)].
- [78] W. Porod, *SPheno, a program for calculating supersymmetric spectra, SUSY particle decays and SUSY particle production at e^+e^- colliders*, *Comput. Phys. Commun.* **153** (2003) 275 [[hep-ph/0301101](#)] [[INSPIRE](#)].
- [79] W. Porod and F. Staub, *SPheno 3.1: extensions including flavour, CP-phases and models beyond the MSSM*, *Comput. Phys. Commun.* **183** (2012) 2458 [[arXiv:1104.1573](#)] [[INSPIRE](#)].
- [80] CMS collaboration, *Search for narrow resonances using the dijet mass spectrum in pp collisions at $\sqrt{s} = 8$ TeV*, *Phys. Rev. D* **87** (2013) 114015 [[arXiv:1302.4794](#)] [[INSPIRE](#)].
- [81] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer and T. Stelzer, *MadGraph 5: going beyond*, *JHEP* **06** (2011) 128 [[arXiv:1106.0522](#)] [[INSPIRE](#)].
- [82] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 physics and manual*, *JHEP* **05** (2006) 026 [[hep-ph/0603175](#)] [[INSPIRE](#)].
- [83] S. Kretzer, H.L. Lai, F.I. Olness and W.K. Tung, *Cteq6 parton distributions with heavy quark mass effects*, *Phys. Rev. D* **69** (2004) 114005 [[hep-ph/0307022](#)] [[INSPIRE](#)].
- [84] CMS collaboration, *Determination of jet energy calibration and transverse momentum resolution in CMS*, *2011 JINST* **6** P11002 [[arXiv:1107.4277](#)] [[INSPIRE](#)].
- [85] B.C. Allanach, S. Biswas, S. Mondal and M. Mitra, *Resonant slepton production yields CMS $eejj$ and ejj missing p_T excesses*, *Phys. Rev. D* **91** (2015) 015011 [[arXiv:1410.5947](#)] [[INSPIRE](#)].
- [86] A.J. Buras, J. Girrbach-Noe, C. Niehoff and D.M. Straub, *$B \rightarrow K^{(*)} \nu \bar{\nu}$ decays in the standard model and beyond*, [arXiv:1409.4557](#) [[INSPIRE](#)].